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August 8, 2019

Via Electronic Filing

Marlene H. Dortch, Secretary
Federal Communications Commission
445 12th Street, SW
Washington, D.C. 20554

Re: Auspion Inc. Request for Wavier, ET Docket No. 19-83
Written Ex Parte Presentation

Dear Ms. Dortch:

Auspion Inc. ("Auspion") submits this letter to clarify certain matters for the docket and to respond to certain issues raised in reply comments in the above-captioned proceeding.[1/]

Auspion's system performs wireless power transfer ("WPT") at a distance with transmission in the millimeter wave bands, higher in frequency than other systems considered by the Commission. At these high frequencies, the smaller wavelength allows modestly sized systems to form beams that are narrow and can be readily steered, and permits rapid power transfer at longer distances compared to those operating at lower frequency bands, all while confining power to a greater degree than systems operating at lower frequencies.[2/] These unique features allow the Auspion technology to transmit meaningful amounts of power to devices in real world conditions, while keeping users safe and controlling for interference to others due to the smaller volume of the three-dimensional space within which the power is contained and the smaller two-dimensional area into which it is sent.

Energous suggests that any waiver granted should be "narrowly tailored" to Auspion's specific request.[3/] Auspion concurs. As discussed further below, the particular facts presented in the Waiver Request,[4/] both with regard to the technology and frequency band used and the proposed conditions of operation, set it apart. These features also make strict compliance with the current interpretation of the Commission's Rules inconsistent with the public interest. In fact, these characteristics make the Auspion request similar to what is presently allowed for WPT in lower frequency bands in terms of the volume of power beams formed, while power energy localization areas are significantly smaller and power is transferred at a greater distance.[5/] For these reasons, the waiver should be granted.

1/ Reply Comments of Energous Corporation, ET Docket No. 19-83 (filed May 10, 2019). *See also* Reply Comments of Ossia Inc., ET Docket No. 19-83 (filed May 10, 2019).
2/ *See* Technical Statement at 1 and 10, attached.
3/ Energous Reply at 2.
4/ Request by Auspion Inc. for Waiver of Section 18.107(c) of the Commission's Rules, OET Docket 19-83 (filed Jan. 3, 2019) ("Waiver Request").
5/ *See generally*, Technical Statement.

Transmission Distance

Auspion would like to clarify information regarding the maximum length of transmissions. Auspion agrees with Energous that the method of determining Part 18 "local" use in the context of WPT need not be confined to examining the distance between the transmitter and the receiver.[6/] In Auspion's view, the generation of energy in the radiative near-field; the volume of RF energy distribution (the area in which RF energy is generated and locally absorbed in the power beam); and the control over the location of power energy localization, combined, can be equally valid means of demonstrating "local" use of RF.[7/]

Nonetheless, the Waiver Request sets out use cases where charging distances can be reasonably specified. Under the Waiver, Auspion's system would operate primarily in indoor environments, such as within an office, a retail location, an industrial floor, or a similar setting. In these use cases, Auspion can provide commercially useful charging at a distance of no more than 4 meters, with security cameras possibly needing 10 meters.[8/] Auspion would be willing to have these limitations on charging distances as a condition of this Waiver Request, though it does not believe that they are inherent to a determination of "local" use.

Auspion's Waiver Request Plainly is Not a Rule Change

The Waiver Request is narrowly focused and not tantamount to a rule change. The Waiver Request focuses on the specific characteristics of, and the proposed use conditions for, the Auspion system, conditions that would not be satisfied by other types of wireless power transfer systems. Therefore, Auspion expects that the particular facts and circumstances relied upon in granting the waiver would not apply to others.

Auspion, like others in the WPT industry, uses multiple antennas arranged as an array system to deliver directionality and provide steerability with an RF beam. Auspion's system differs in the frequency band used. In particular, the significant difference in frequency allows for use of a greater density of elements, and thus power transfer is achieved with a transmitter and receiver(s) which sizes are appropriate for real-world application. The specific unique characteristics of Auspion's technology and the Waiver Request include:

- The 24 GHz millimeter wave frequency allows for a much greater density of much smaller antenna elements.
    - This can accomplish significant power delivery in "real world" settings, where the transmitter and receiver(s) are appropriately sized (*i.e.*, one-third of the size of a ceiling tile and small enough to fit into a smartphone, respectively).
- Meaningfully smaller power energy localization can be achieved because of the significantly smaller wavelengths in the 24 GHz frequency.

6/ *See* Energous Reply at 5-6.

7/ In fact, the power energy localization and volume of energy distribution achieved by the Auspion system at 24 GHz likely were not considered when the Commission staff originally considered "local" in relation to distance.

8/ As discussed below and in the attached Technical Statement, Auspion intends to demonstrate in appropriately designed RF safety testing that safety will be achieved.

- For the same size antenna array, the power energy localization generated by Auspion's 24 GHz system would be significantly smaller than for a system designed for the 900 MHz, 2.4 GHz, or 5.8 GHz bands.[9/]

- Use of a more controlled and steerable beam, at a higher frequency, can place the power more precisely, and at various angles and depths not achieved in lower frequencies.
- Coupled with the beam steering technologies, Auspion's system allows the formation of comparable power beam volume, while transmitting at a much greater distance (4 m vs. 1 m) than systems operating in lower bands (assuming an equivalent transmitter).[10/]
- Proposed conditions would limit use to when the receiving device is not being held or worn by a person.
- Proposed condition would limit sales to non-consumer users (*e.g.*, retail, industrial, enterprise).
- Proposed condition would require professional installation.

For these reasons, the Waiver Request is **not** a request to make a blanket change to the present rule, as it is interpreted.[11/] The Request is quite similar to other technical waivers granted by the Commission where the Commission has determined that a party's specific technical characteristics and proposed use case are distinct from others.[12/] In these situations, upon a finding of good cause that such a waiver is in the public interest, the Commission has granted the waiver request, determining that such a request is distinct from a rule change.[13/]

Auspion also notes that the Commission has recognized that economic harm to start-up companies delayed in getting to market while awaiting an FCC rule change can be a reason to grant a waiver. For example, the FCC granted a waiver to a company to market non-compliant anti-theft devices "to build up a business at its own risk while the rulemaking was pending."[14/] The Commission explained that it was "unrealistic to expect the company to stay in business for a period of 2-3 years without a saleable product while the merits of the revised rule are argued."[15/] The Commission determined that it was reasonable to grant a waiver pending a rulemaking when the waiver petition set out a reasonable prospect that the technology might provide the user with more

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9/ *See* Technical Statement at Section 1b and Figure 1.

10/ Technical Statement at 2-3 and 9-10.

11/ As Auspion has explained, it does not believe that a waiver request is necessary, but it is proceeding under the understanding that Commission staff currently interprets "local use" to be approximately one meter in distance.

12/ *See* K*yma Medical Technologies, Ltd Request for Waiver of Part 15 of the Commission's Rules Applicable to Ultra-Wideband Devices*, Order, 31 FCC Rcd 9705 (2016) (determining that various industry waivers of a technical rule, each focused on the specific characteristics of and proposed use case for a specific device, are distinct from a requested rule interpretation applicable to all manufacturers that would effectively amount to a rule change); *MTS and WATS Market Structure; Applicability of Certain Access Charge Provisions to Certain Resold MTS/WATS and MTS/WATS-Type Services*, Memorandum Opinion and Order, 61 Rad. Reg. 2d (P & F) 417 at ¶ 12 (1986) (a waiver limited both in time and services affected is not a request requiring a general rule change).

13/ *Id*.

14/ *Amendment of Part 15 to Provide for the Operation of Wide-Band Swept RF Equipment Used as Anti-Pilferage Devices*, Notice of Proposed Rulemaking and Order Denying Petition for Reconsideration, 59 F.C.C.2d 1256 at ¶ 29 (1976) ("Swept RF Waiver").

15/ *Id*.

effective, lower cost and less interfering equipment.[16/] Similar considerations exist here. For example, the Auspion system will charge more efficiently and will not impede the operations of other users.

Auspion's Request is Equivalent to What is Presently Allowed

Auspion's Waiver Request does not seek permission to do more than what the Commission currently allows. Through its pre-approval KDB process, which is required for frequency exposure review of all WPT products, the Commission has allowed commercialization of several types of WPT systems operating in the 900 MHz, 2.4 GHz, and 5.8 GHz bands.[17/] These systems provide power at distances of up to three feet (approximately 1 m).

The attached Technical Statement demonstrates that Auspion's system operating at 24 GHz and at a distance of 4 m uses smaller power energy localization and equivalent power beam volume – posing no greater risk than what the Commission has approved at lower frequency ranges, such as 900 MHz, 2.4 GHz and 5.8 GHz. The Commission should not subject Auspion to different performance-based requirements simply because it uses different spectrum.[18/]

Operating at 24 GHz allows Auspion to generate smaller power energy localization and comparable power beam volume transmitting at greater distances than these approved systems.[19/] For example, at 900 MHz, a wireless power transfer system transmitting at a distance of 1 m creates energy localization sizes (radius) equivalently the same as a 24 GHz system transmitting at a distance of 4 m.[20/] In addition, the range of a WPT system increases proportionally with the frequency of operation. In other words, in terms of volume of the power beam and size of power energy localization, 1 m at 900 MHz, 2.4 GHz or 5.8 GHz is equivalent to 4 meters at 24 GHz for otherwise the same physical system sizes (transmitter and receiver). For these reasons, while other systems operating in lower frequencies have been allowed to transfer power up to 1 m in distance, Auspion can transfer power up to 4 meters and be just as "local" in terms of power energy localization and power beam volume.[21/]

Safety Features and Testing

The Commission allows many different types of higher power transmitters to emit high RF energy fields – significantly higher than what is contemplated here – so long as those transmitters meet the appropriate safety standards.[22/] The same should be true for Auspion. If Auspion can demonstrate that its system will measure its environment and engage in sensing for RF safety, and

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[16/] Swept RF Waiver at ¶ 30.

[17/] *See, e.g.*, FCC ID Nos. 2AS57OSSIACOTATX201 (Ossia); 2ADNG-MS300A (Energous); YESTX91503 (Powercast).

[18/] A showing of unique circumstances in support of a waiver can include a showing of inequity to justify departure from a rule. *See Petition for Waiver of the Commission's Rules to Recover Network Depreciation Costs*, Order, 9 FCC Rcd 377 (1993).

[19/] *See* Technical Statement at 1-3 and 9-10.

[20/] Technical Statement at 10.

[21/] *See* Technical Statement at Section II for a more detailed discussion of achievable power spot size.

[22/] *See e.g.* 47 C.F.R. § 73.49 (fencing requirements for AM radio base stations).

otherwise meet the Commission's safety standards, its technology should be deemed equally safe as other systems.

Auspion intends to obtain a grant of equipment certification, meaning it will engage in the KDB process, allowing Commission staff to engage in the development of appropriate test procedures for the system. This process will include submission of a test plan so that the Commission will be confident that the system will be fully and properly tested to demonstrate that it meets all RF safety requirements prior to going to market.

As Auspion explained in its Waiver Request, its system will have multiple, independently testable safeguards that will ensure safe operations, including "multiple active and passive functionalities, such as location determination and sensing, that allow it to sense and react to the presence of people and other objects in a highly accurate manner."[23/] The system will also have multiple shut off mechanisms.[24/] For example, it will shut off within 100 milliseconds when communication or power loss is detected.[25/] Other safety features include evaluating the orientation of the device being charged (including whether it is moving, fixed, or set on a stable surface) and passively sensing nearby movement and beam interruption through detection of people or other objects nearby. As Auspion explained, "[i]n this way, the distances between the beam, the charging device, and any people located in the vicinity can be calculated in milliseconds, ensuring that the power transfer will cease before a person enters the path of a beam."[26/] These features will also be native to the system.[27/] In sum, the system will not have a single point of failure that could result in any harm.

For these reasons and those already set out in the record of this proceeding, it is appropriate for the Commission to grant Auspion's Wavier Request.

23/ *See Request by Auspion Inc. for Wavier of Section 18.107(c) of the Commission's Rules*, OET Docket 19-83, at 2 (filed Jan. 3, 2019) ("Waiver Request"). For example, the system will feature interlocks that turn off or greatly reduce beam power when a human or pet enters the small high power flux density zone.

24/ Waiver Request at 5.

25/ Waiver Request at n. 12.

26/ Waiver Request at 6.

27/ *Id*.

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Please direct any questions to the undersigned.

Sincerely,

/s/ Laura A. Stefani
Laura A. Stefani
Counsel to Auspion Inc.

cc: (each *via* email)
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Technical Statement
Auspion Wireless Power Transfer System

1. Executive Summary

This document addresses the operation of Auspion's Wireless Power Transfer system (the "system") in light of a Waiver Request filed with the FCC[1]. It concludes that the high frequency of operation of this system allows it to generate smaller power energy localization and comparable power beam volume, at significantly greater distances of transmission, as systems that the Commission has allowed to operate at up to 1 meter transmission distance in lower frequency bands. It also demonstrates that the system operates "locally," in the radiative near-field.

a. System description.

The Auspion system utilizes an array of hundreds or thousands of 24 GHz RF transmitters to create an RF lens, focusing (or "localizing") energy in a small focal plane area at distances of four or more meters. The area of this focal plane (or localization area) can be quite small, so as to permit the required energy recovery array of elements to be mounted on or incorporated into the powered device, even if such device is small (e.g., a smartphone or security camera).

The transmitter also includes a parallel array of receivers, to permit sensing functionality for use in advanced safety features.[2]

Localization and safety interlocks are enabled via a complex RF beam formation and control algorithm, which monitors objects in the power space, power levels at both ends, and movement of either transmitter or receiver, and manipulates phase and amplitude of individual transmit elements in real-time.

b. Equivalent spot size at greater distance.

Because Auspion is using a mm-wave frequency, its system concentrates RF energy as "locally" as currently allowed systems. As we detail in this report, with everything else being equal, the energy localization sizes (radius) are proportional to the wavelength employed and inversely proportional to the frequency of operation. In addition, a system using a wavelength λ cannot achieve an energy localization size smaller than $\lambda/_4$. As a result, Auspion's system confines RF energy to comparable areas and volumes over much larger distances as systems operating at lower frequencies.

To visualize the impact of the choice of operating frequency on power localization, we compare in Figure 1 four systems in terms of their performance over distance. All transmitters have a circular aperture of 20 cm, operating at the following frequencies: 900 MHz, 2.4 GHz, 5.8 GHz and 24 GHz. As can be seen

[1] *Request by Auspion Inc. for Wavier of Section 18.107(c) of the Commission's Rules*, OET Docket 19-83 (filed Jan. 3, 2019) ("Waiver Request").

[2] As noted in the Waiver Request, the system will have multiple, independently testable safeguards, the specific operations of which will be submitted via the Commission's KDB process for test configuration.

from the figure, the use of higher frequencies results in much smaller power energy localization size (radius), all else being equal. In addition, as discussed next, systems at higher frequencies create equivalent beam volume while transmitting at greater distances.

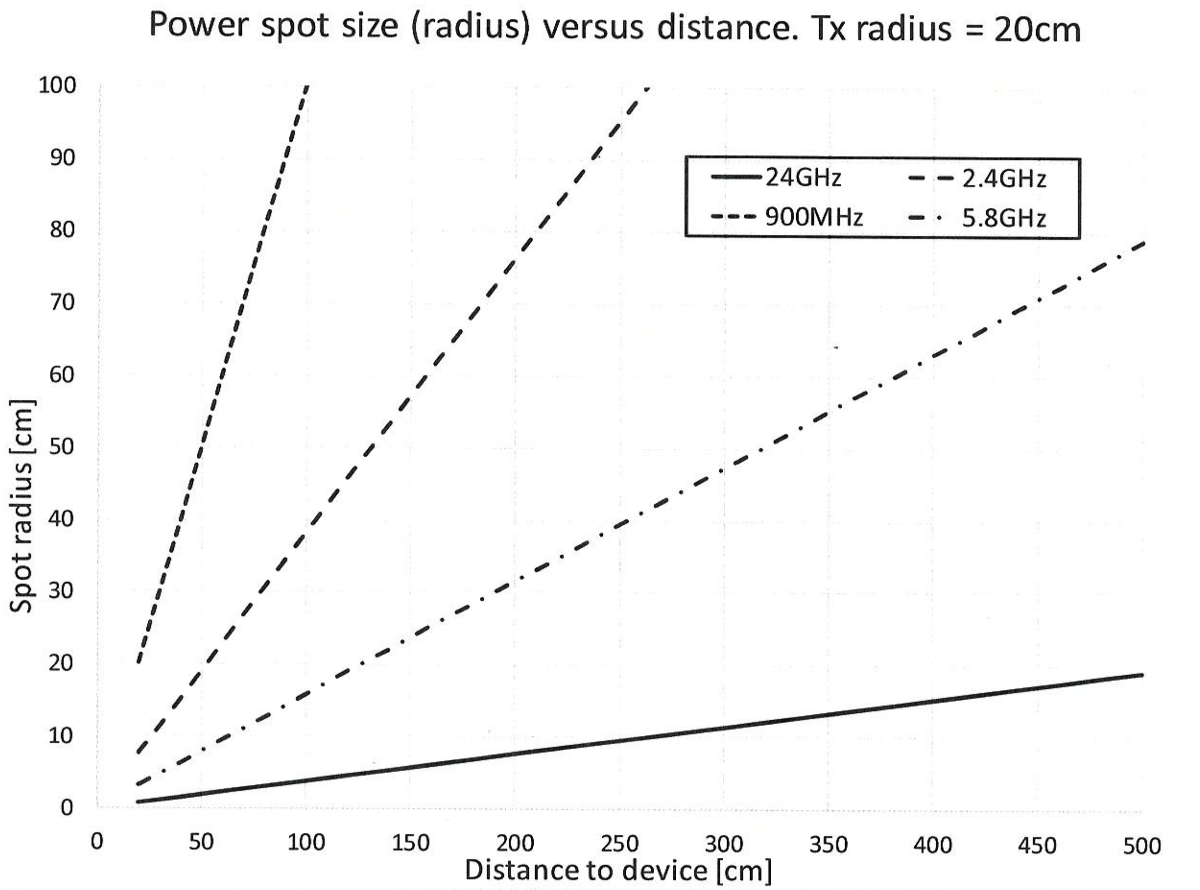

Figure 1 – Power energy localization sizes versus distance for four system, each with a transmit aperture of 20 cm. The systems operate at 900 MHz, 2.4 GHz, 5.8 GHz and 24 GHz, respectively.

c. Equivalent beam volume at greater distance.

In addition to creating much smaller energy localization sizes, the beam volume of RF energy produced by Auspion's system operating at 24 GHz and at distances in excess of four meters is comparable to the RF energy distribution of a system operating at 900 MHz and at a range of one meter. This is because, everything else being equal, for a given energy localization size, the area of the transmitter increases proportionally to the square of the wavelength used, i.e. it is inverse proportional to the square of the operating frequency.

For illustration, systems operating at lower frequencies than 24GHz need to be significantly larger to achieve the same energy localization sizes. For a 24 GHz system with an area of 1260cm^2 (about the third of the size of a standard ceiling tile), a 5.8 GHz system would have occupy an area of 21,500cm^2 (the size of a door frame), a 2.4 GHz system would be the size of a room (125,500cm^2, 10 x 14ft), and a 900 MHz system would occupy 890,000cm^2 (approximately one and a half times the size of an average highway billboard). Aside from practical considerations, these lower frequency systems would also fill a much larger volume between the transmitter and the receiver with RF energy. For visualization, we show the relative sizes of the transmitter antenna array in comparison in Figure 2.

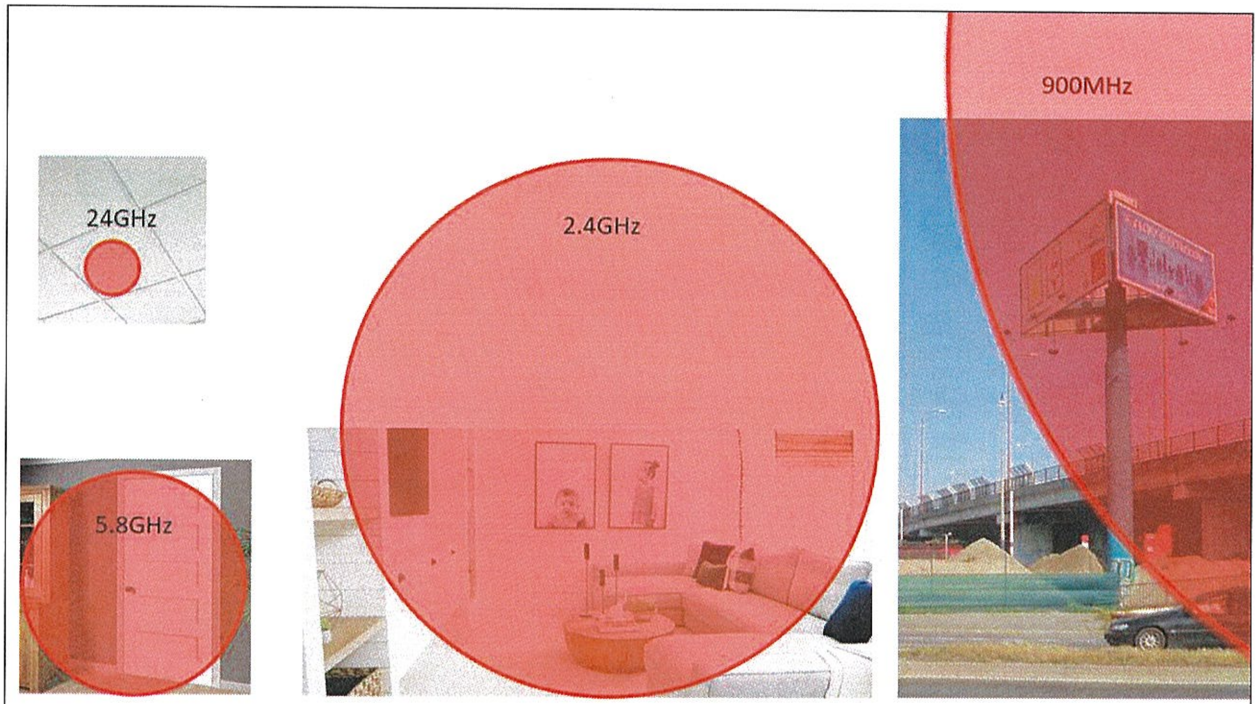

Figure 2 – Relative physical size comparison of wireless power transfer systems operating at 24 GHz, 5.8 GHz, 2.4 GHz and 900 MHz.

Summarizing the effects of frequency on key metrics for wireless power transfer systems, Figure 3 indicates the localization of energy and power beam volume. The transmitter localizes the RF energy in 3D-space (symbolized by the coordinate axes), creating a power spot in the distance. RF energy is localized in the conical area between the transmitter (shown in light green) and the power spot (shown in orange). As Auspion demonstrates herein, a system operating at 24 GHz produces significantly smaller power energy localization and a comparable volume of RF energy distribution at significantly greater distances of transmission (approximately 4 m) as compared to systems that the Commission has allowed to operate at up to 1 m transmission distance in lower frequency bands. *See* Technical Section at ii (Volumetric confinement of RF power in Auspion's system).

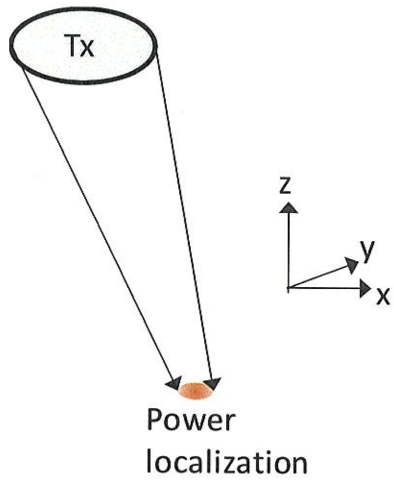

Figure 3 – Stylized system operation. Transmitter is shown in light green, creating a power spot at a distance.

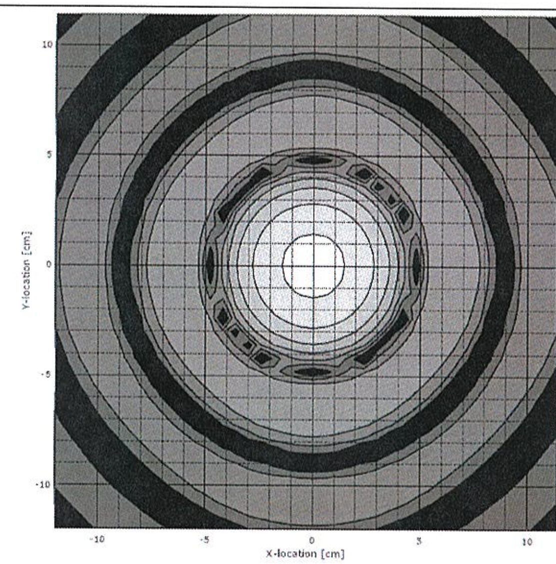

Figure 4 – Example Airy pattern generated by a finite antenna array for maximum power intensity at center (bright: larger intensity, dark: lower intensity).

2. Technical Discussion

a. The Auspion system.

The system consists of at least one transmitter (*generation unit* or *GU)* and one receiver device (*recovery unit* or *RU*). The transmitter transmits power via an antenna array. Systems requiring larger distances, tighter power energy localization, higher transmitted power or any combination of these will utilize a transmitter that can have many thousands of individual antennas. The antennas are arranged in an array, where the phase and amplitude of the radiated RF power can be individually controlled.

During normal operation, the system will localize the RF energy into a spot in 3D space (*see* Figure 3) in the same way that an optical lens focuses light onto a spot in space. Thus, the system operates "locally," or in the radiative near-field, as the RF energy would first converge onto the point in space and then start diverging. This is different from how a traditional phased array operates, which is understood to create a desired far-field pattern (which corresponds to a localization depth of infinity). In addition, the amplitude of each antenna is controllable to allow additional control over the exact shape of the power energy localization spot[3].

The system is not limited to this type of operation, and can, just like a more traditional phased array, create multiple beams, make use of reflecting surfaces, and pre-distort the pattern in the near-field to counteract distortion created by an object in the path (typically a cell phone case or the GU case itself), among other benefits. When the RU aperture is physically larger than the tightest energy localization

[3] In optics, this would correspond to an *apodized* lens. *See* https://en.wikipedia.org/wiki/Apodization.

size that can be created, the system will create a spot that utilizes the whole area rather than the tightest energy localization sizes physically possible. The system is thus highly adaptive. The adaptive nature of the system enables intelligent control of the electromagnetic waveform concentration.

b. Physics of RF based wireless power transfer systems.

i) Achievable power energy localization sizes.

For the following discussion, we will discuss system operation for energy localization, as this is the limit of what any system that uses RF to power at a distance can achieve. We will quantify the size of the energy localization point by its radius or area for the remainder of this document. The achievable level of localization in any electromagnetic system is limited by diffraction. We will discuss two types of diffraction limits that are applicable: the *Fraunhofer Diffraction Limit* of a circular aperture and the *Abbe Diffraction Limit*[4].

1. Fraunhofer Diffraction Limit.

In deriving the physical limits of a transmitter array such as our GU, we consider a circular aperture (antennas arranged in a nearly circular fashion) of radius r. We assume that the element antennas are spaced at half-wavelength[5]. For a wavelength λ and a localization distance D reasonably far away[6], any system is limited by what is known as Fraunhofer Diffraction[7]. When all antennas emit power of the same magnitude (no *apodization*), the resulting intensity pattern at the localization plane is known as an *Airy* pattern (Figure 4), which is radially symmetric and has an intensity given by[9]

$$I(w) = I_0 \left(\frac{2J_1(krw)}{krw} \right)^2$$

where I_o is the peak intensity, J_o is the so-called Bessel function of the first kind of order one, $k = \frac{2\pi}{\lambda}$ is the wavenumber and w is the sine of the observation angle. In terms of radial distance x from the center of localization, this can be rewritten as

$$I(x) = I_0 \left(\frac{2J_1\left(\frac{2\pi r}{\lambda D} x\right)}{\frac{2\pi r}{\lambda D} x} \right)^2$$

The peak intensity is given by[10]

$$I_0 = \frac{P\pi r^2}{\lambda^2 D^2}$$

where P is the emitted power.

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[4] The Abbe Limit is a special case of Fraunhofer diffraction, and was originally derived for the resolution of optical microscopes. Compare M. Born, E. Wolf, "Principles of Optics," 7th (expanded) ed., Cambridge, UK, p.467ff.

[5] For larger spacings, grating lobes will occur limiting the performance of the array. For spacings smaller than half-wavelength, the gain of the individual antennas becomes aperture limited, meaning that the effective aperture is already at its achievable maximum.

[6] To be specified further below.

[7] https://en.wikipedia.org/wiki/Fraunhofer_diffraction.

[9] M.Born, E.Wolf, "Principles of Optics," 7th (expanded) ed., Cambridge, UK, p.440.

[10] Same.

This pattern consists of light and dark regions, with the first minimum, or "dark," ring occurring at a radial distance $x_1 \cong 1.22\frac{D\lambda}{2r}$ (compare the first "null" of power where the main lobe ends). No pattern with higher peak intensity is possible. However, it is possible to increase the size of the center spot while reducing or eliminating the intensity in the side lobes (e.g. through *apodization*). For an ideal Airy pattern, the peak intensity in the first side-lobe is approximately 1.8% of the peak intensity I_0. For practical localization patterns, the peak intensity can be (much) lower.

This regime of operation is called the *Fraunhofer Diffraction limit* and applies to systems where the localization distance is reasonably far away. More specifically, reasonably far away means that the so-called *Fresnel Number* of the system is greater than one. The Fresnel Number is defined as[11]

$$F = \frac{r^2}{D\lambda}$$

and it is greater than one for localization distances

$$D > \frac{r^2}{\lambda}$$

As can be gathered from the above discussion, operating at higher frequencies and smaller wavelength results in smaller energy localization sizes, for the same physical aperture (size).

Further insight can be gained by taking wavelength out of the equations above and making it implicit by considering the number of antennas used. Since we assumed that the antenna spacing is $\frac{\lambda}{2}$, the *area per antenna* is $\left(\frac{\lambda}{2}\right)^2$. We also note that a circular aperture of radius r has an area of πr^2 and hence the number of antennas in that area is

$$N = \frac{4\pi r^2}{\lambda^2}$$

and we can write

$$\frac{\lambda}{r} = \sqrt{\frac{4\pi}{N}} \approx \frac{3.54}{\sqrt{N}}$$

Thus, the distance to the first dark ring (i.e., minimum with no power) in the pattern can be expressed as

$$x_1 \approx 1.22\frac{D\lambda}{2r} \approx \frac{2.16}{\sqrt{N}}D$$

We note that the distance to the first dark ring grows linearly with the localization distance as expected. We also note that systems operating at different frequencies - *in the Fraunhofer Limit* only, though - generate the same energy localization size. In reverse, however, in order to generate an energy localization spot of a certain size, the same number of antennas must be used, and operating at a higher frequency of operation allows the system to be smaller in area by the square of the ratios of the wavelengths. Moreover, the Fraunhofer Limit is applicable for localization distances greater than

[11] M.Born, E.Wolf, p.417. The Fresnel Number is the number of so-called Fresnel zones in the aperture.

$$D > \frac{r^2}{\lambda} = \frac{r^2}{\lambda^2}\lambda = \frac{N}{4\pi}\lambda$$

Thus, systems using N antennas operating at shorter wavelengths operate in the Fraunhofer region for shorter localization distances compared to systems using longer wavelengths. This is relevant for the Abbe Diffraction Limit, discussed next.

To summarize, Figure 4 depicts an ideal Airy pattern power distribution as a 2D plot. The Airy pattern is the limit of power distribution for maximal power intensity localization the center (a "best focus") of a circular aperture. This limit pattern applies to all wireless RF based power systems. That is, no RF (or light) based system can achieve higher concentration of power around the center locale. It demonstrates that power intensity is high at the place of localization (main lobe) and drops off quickly. The exact distribution can be modified by making the central peak somewhat broader, lowering the peak intensity, but also reducing the distribution outside the main lobe. The theory of Airy patterns demonstrates the limits to achievable localization sizes for systems operating at different frequencies. Operating at a high frequency is advantageous for operating "locally."

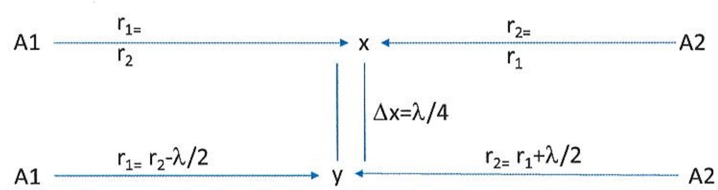

Figure5– Diagram illustrating localization limit $\lambda/4$ (upper limit)

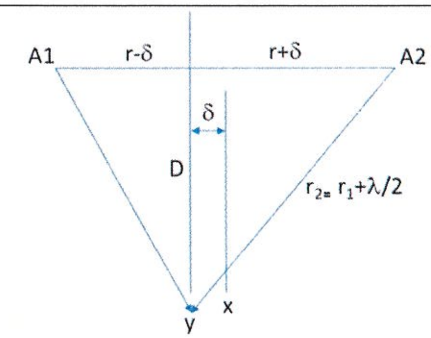

Figure 6– Diagram illustrating localization limit for a transmitter system (upper limit)

2. Abbe Diffraction Limit.

When the localization distance becomes too short or wavelengths and apertures become large become large – the energy localization sizes predicted by Fraunhofer Diffraction is *optimistically* small, i.e. it is in reality larger as the energy localization sizes cannot be smaller than

$$s = \frac{\lambda}{2n\,\sin\theta}$$

where n is the index of refraction (for air: 1), and θ is the half angle of the localization cone (i.e. less than 90°). Thus, no RF wireless power system operating in air can achieve better energy localization sizes less than $\lambda/2$. This can be understood by considering (*see* Figure 5) a pair of antennas A1 and A2 adding constructively at a localization point "x" situated half-way between them. At the localization point, the fields add constructively. In order to reach the first null "y", we would have to move a distance $\lambda/_4$ away from the point x, for the field of the first antenna to advance by 90°, the field of the second antenna to retard by 90° and thus the phase difference to be 180° (such that the total field is zero). By moving these antennas in the y-direction, it's clear that the *difference* in distances r_1 and r_2 is smaller than $\lambda/_2$ (or 180°), and hence the first null cannot be generated closer than $\lambda/_4$.

Thus, operating at shorter wavelengths, smaller energy localization sizes become physically possible.

We can use this argument (*see* Figure 6) to estimate the energy localization sizes for short localization lengths, by solving $\sqrt{D^2 + (r+\delta)^2} - \sqrt{D^2 + (r-\delta)^2} = \frac{\lambda}{2}$ for δ, the distance to the first null. There is no closed-form solution, but we will solve the equation numerically in later examples. For r approaching infinity (or, correspondingly, D approaching zero), the limit of the distance to the first null is $\frac{\lambda}{4}$.

It should be noted that the limits derived are an optimistic limit and that the actual (minimum) energy localization sizes will be (slightly) larger. This is because we have used the outer antennas to create a first null, which provide the highest resolution. Antennas arranged closer to the center will not be able to resolve with that accuracy.

Born et al. provide the following limit first derived by Abbe for the resolution of a microscope (which is applicable in this case as well) using coherent illumination[13]:

$$s = 0.82 \frac{\lambda}{n \sin\theta}$$

where n is the index of refraction of the medium and θ is the angle from the aperture edge to the focal point. Thus, in air, the expected minimum energy localization sizes will be closer to the length of a wavelength.

Including the effect of Abbe Diffraction, Figure 7 shows the achievable localization sizes for systems operating at 900Mhz, 2.4GHz and 24GHz for a transmit (GU) aperture size of 40cm at various distances.

[13] M.Born, E. Wolf, pp. 471.

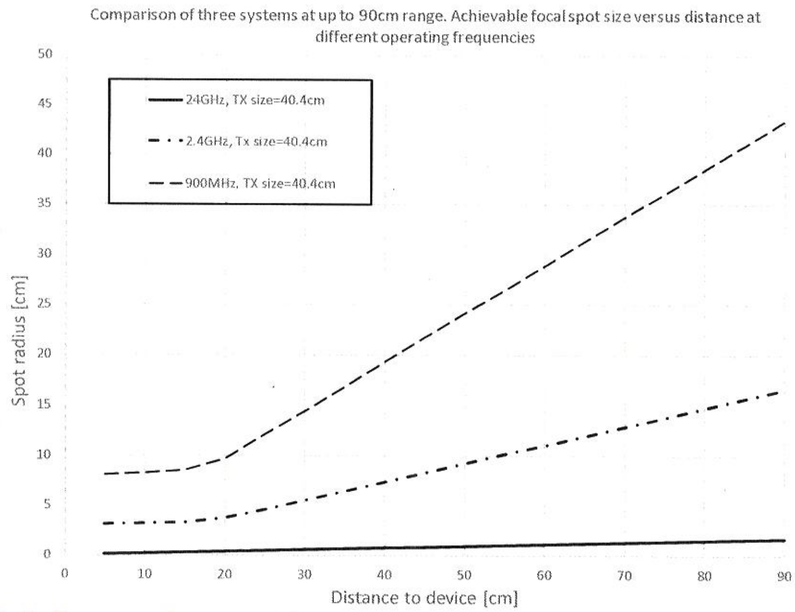

Figure 7 – Performance of systems with 5,000 cm2 aperture operating at 900 MHz, 2.4 GHz, and 24 GHz

ii) Volumetric confinement of RF power in Auspion's system.

The FCC rules require local use of RF power by ISM equipment[14]. For the systems discussed, we briefly compare the confinement of RF power both in energy localization sizes as well as volume in space. For our comparison, energy localization sizes achievable for systems with an aperture of 5,000cm^2 or 40 cm/16" diameter operating at 900 MHz, 2.4 GHz (comparable to previously authorized equipment) and 24 GHz (for comparison) are shown in Figure 7. We observe from Figure 7 that a system operating at 900 MHz creates energy localization sizes (radius to first null) at a distance of 90cm (three feet) for a system size (radius) of 40 cm (1.3 feet), comparable to the size and performance of recently granted equipment authorization for RF based wireless power transfer under Part 18.

A system designed for charging within a room and operating at 24 GHz (which physically would be a quarter of the size of a 2.4 GHz system, as described above), achieves the same power energy localization size at a distance of 4 m (12 feet). In addition, since RF power is transmitted in a beam, the vast majority of it is confined to a truncated cone starting at the transmitter and ending at the receiver. In the case of a 900 MHz short-range system transmitting at a distance of 90cm (3 feet) away, the volume occupied by the cone is

$$s = \frac{1}{3}\pi(r_1^2 + r_1 r_2 + r_2^2)h = 0.452m^3$$

with $r_1 = 40cm$, $r_2 = 40cm$ and $h = 90cm$. For a system at 24 GHz, the volume occupied by RF energy is *less* at $0.387m^3$ when operating at a transmission distance of $4m$, and would be equal when operating at a transmission distance of $4.35m$. **Compared to a 900 MHz system operating at short distances of 90cm or less, Auspion's system at much longer transmission distance (>4 m) would**

[14] 47 C.F.R. § 18.107(c).

confine power to an extent comparable to short range systems operating at 900 MHz at the shorter (1 m) transmission distance.

iii) Summary and Key Points.

From the above discussion, we note the following key points:

1. Everything else being equal, the power energy localization sizes are proportional to the wavelength employed and inversely proportional to the frequency of operation.
2. Everything else being equal, for localization distances "far" from the aperture, the minimum achievable energy localization sizes (area) grows as the square with the distance, while the radius is directly proportional to the distance.
3. Everything else being equal, for a given power energy localization size, the size (area) of the transmitter increases as the square with the wavelength used, i.e. it is inversely proportional to the square of the operation frequency.
4. The minimum achievable energy localization size (radius) increases linearly with localization distance for "far" ranges.
5. A system using a wavelength λ cannot achieve an energy localization sizes smaller than $\lambda/_4$.

From the above, it follows that a high frequency of operation is desirable to achieve small energy localization sizes, avoid unnecessary power spill-over and to make systems physically small. We also note that the limits discussed above are generally applicable to all RF based wireless power systems, as they were derived from physical principles.

None of what is stated above precludes operation utilizing multiple beams, reflections off walls and other surfaces, diffraction around corners, among others. None of these modes of operation inherently changes the system behavior or what is achievable. For example, when reflections are used to avoid obstacles in the beam path, the same considerations still hold true except that parameters such as distance to the localization point may be different.

For the reasons described, Auspion is building systems at mmWave frequencies, in particular 24 GHz, to achieve useful form factors and system efficiencies.

* * *

I declare under penalty of perjury under the laws of the United States of America that the foregoing is true and correct to the best of my knowledge. Executed on the 7th day of August, 2019.

Florian Bohn, Ph.D.
Co-founder, Board Member and VP of Engineering
Auspion, Inc.